AIR WAR COLLEGE

AIR UNIVERSITY

A WEB OF DRONES:

A 2040 STRATEGY TO REDUCE THE UNITED STATES DEPENDANCE ON SPACE BASED CAPABILITIES

by

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Biography

Colonel James Morgan "Kawg" Curry is assigned to the Air War College, Air University, Maxwell AFB, AL. Colonel Curry graduated from the United States Air Force Academy in 1993 with a degree in Astronautical Engineering and a minor in Russian. He earned his pilot wings at Columbus AFB, MS and went on to become an instructor pilot in the KC-135. Following his time in the tanker, he returned to Undergraduate Pilot Training to become an instructor pilot in the T-37 Tweet at Laughlin AFB, TX. For his first staff assignment, he worked at the National Geospatial-Intelligence Agency in Bethesda, Maryland where he acted as a counterterrorism liaison between the agency and special operations forces. Colonel Curry then put his newfound intelligence experience to use and joined the 17th Reconnaissance Squadron at Creech AFB, Nevada, where he became fully qualified in both the MQ-1 Predator and the MQ-9 Reaper. He culminated his three years in the Unmanned Aerial System community with a command tour in Afghanistan. During his tour in the desert, his squadron's operations tempo nearly doubled and he conducted numerous site surveys enabling further expansion of the unmanned enterprise in Afghanistan.

Upon his return from overseas, Colonel Curry spent four years on the Air Staff at the Pentagon where he worked in various areas to include Air Force Checkmate and the Chief of the Action Group for the Deputy Chief of Staff for Operations, Plans, and Requirements (A3/5).

Abstract

Do not believe the myth that certain space-based capabilities can only be achieved from space. Space certainly has a litany of characteristics that make it the ideal location to conduct operations. Space has global persistence that requires very little energy to maintain once a satellite is in orbit. Space allows access to denied territory. Space is cost effective when a global scale is required. But space is becoming a more vulnerable environment. Not only do satellites have to survive in the harsh environment of space, but now they are more vulnerable than ever to a host of man-made hazards such as debris fields, direct ascent anti-satellite weapons, and ground based lasers. Space risk used to focus on the launch phase; and once in orbit, the "sanctuary of space" would ensure the capability would persist. Now an adversary's actions add additional risk to mission success. The US acknowledges this risk, but focuses its mitigation efforts primarily in the space domain because it believes there are certain capabilities that can only be achieved from space. This paper challenges that belief by using air assets to complement and temporarily replace key space services.

By the year 2040, space will become even more critical to mission success than today, and at the same time more vulnerable. To provide an alternative to these critical space services, this paper posits that in a denied space environment, a fleet of unmanned, autonomous drone aircraft whose primary mission is to form an interconnected web over the battlefield will provide the critical warfighting services of precision navigation and timing (PNT), command and control (C2), and intelligence, surveillance, and reconnaissance (ISR).

Chapter 1: Introduction

Do not believe the myth that certain space based capabilities can only be achieved from space. Space certainly has a litany of characteristics that make it the ideal location to conduct operations. Space has global persistence that requires very little energy to maintain once a satellite is in orbit. Space allows access to denied territory. Space is cost effective when a global scale is required. But space is becoming a more vulnerable environment. Not only do satellites have to survive in the harsh environment of space, but now they are more vulnerable than ever to a host of man-made hazards such as debris fields, direct ascent anti-satellite weapons, and ground based lasers. Space risk used to focus on the launch phase; and once in orbit, the "sanctuary of space" would ensure the capability would persist. Now an adversary's actions add additional risk to mission success. The US acknowledges this risk, but focuses its mitigation efforts primarily in the space domain because it believes there are certain capabilities that can only be achieved from space. This paper challenges that belief by using air assets to complement and temporarily replace key space services.

Thesis

By the year 2040, space will become even more critical to mission success than today, and at the same time more vulnerable. To provide an alternative to these critical space services, this paper posits that in a denied space environment, a fleet of unmanned, autonomous drone aircraft whose primary mission is to form an interconnected web over the battlefield will provide the critical warfighting services of precision navigation and timing (PNT), command and control (C2), and intelligence, surveillance, and reconnaissance (ISR). The details of this web will be described in Chapter 5, but as capabilities, cost, and vulnerabilities of space are analyzed in Chapter 2, 3, and 4, consider if space is the only way to deliver these capabilities. The Web of

Drones (WoD) described in Chapter 5 will require certain technologies such as airborne, high bandwidth, laser communication and autonomous air refueling. Will the costs and risks of pursuing these technologies provide an effective counter to the risks of the future space environment? The analysis in Chapter 5 supports the WoD as a cost effective risk worth taking.

Space truly is the ultimate high ground. But even high ground can become vulnerable. Instead of focusing solely on space, a web of drones may provide redundancy in PNT, C2, and ISR in a future environment where the security of space is questionable.

Chapter 2: Space is Essential

Space based services impact nearly every person on earth. From satellite television to navigation to the imagery used to make moving maps, space is increasingly becoming a part of everyday life. Gen William Shelton, former commander of AF Space Command (AFSPC), believes "all military operations, from humanitarian operations all the way to major combat operations, now depend on space, maybe critically so."[1] During Congressional testimony, Lt Gen Richard Formica, head of the Army's Space and Missile Defense Command stated, "virtually every Army operation relies on space capabilities to enhance the effectiveness of our force — there is no going back."[2] Three key space capabilities are the Global Positing System (GPS), satellite communications (SATCOM), and Intelligence, Surveillance, and Reconnaissance (ISR). The capabilities these provide are the core services the WoD is envisioned to complement when space is available and replace when space is denied.

GPS: Never having to ask for directions

GPS has become more than a location tool. GPS is an essential aspect of military, commercial, and civil life. When thought of as a service, the GPS constellation provides timing signals from space used to triangulate a position. The miniaturization of the GPS receiver down to the size of a wristwatch or smartphone has created a population of millions of users who rely on GPS daily. Not only does GPS provide position, but GPS's delivery of a standardized time has created innovations well beyond the constellation's original intent. Optical network switches capable of transmitting 40 gigabytes of data a second rely on time synchronization to ensure the data "flows" seamlessly from one point to another. GPS allows different networks to talk to each other by referencing the same clock. Without this synchronization, the modern internet would cease to function. Bank transactions, data and phone communications, and access to databases would be severely if not totally impaired.[3] GPS has become vital.

SATCOM: Always connected

Reliance of satellite communications (SATCOM) continues to grow despite the proliferation of fiber based communications systems. There are currently 638 satellites providing communication services to nearly everyone on earth.[4] Most large military aircraft have some form of SATCOM radio allowing for real time command and control. The Air Force uses a relay from a communications satellite to control its remotely piloted aircraft from bases in the United States. When a forward operating base is established, a satellite data link is one of the easiest ways to get communication and data flowing. Satellite communication is an essential aspect of worldwide operations.

ISR: The eyes and ears in the sky

Space sensing satellites either actively or passively image the earth or collect electromagnetic intelligence. Large imaging satellites take optical and infrared images. Radar imaging satellites can see through clouds and allow for the accurate mapping of the earth's surface. Signals intelligence satellites listen to electromagnetic waves. Early warning satellites such as the space based infrared system (SBIR) can quickly detect the signatures of rocket launches. The key characteristic of all of these sensing satellites is their ability to access the target. In order to take an image of a target, the sensor has to get overhead. Since the 1960's when the Soviet Union proved it could shoot down a U2 spy plane flying over its country, space has been the ultimate high terrain where all countries are allowed nearly limitless freedom of action. The Air Force flies an array of mid to high altitude aircraft that can accomplish similar sensing mission, but space is the only place to gain access to another country's sovereign terrain.

Political Science professor Alan Steinberg analyzed the US dependence on space and found six key areas including military communications, missile defense, weather, and ISR.[5] The US is well aware of its dependence on space. A Congressional Report stated "the US's increasing economic and military dependence on space creates a vulnerability that is an attractive target for our foreign adversaries."[6] How the US reduces this dependence represents a major strategic decision facing the US.

Chapter 3: Space is Expensive

During the height of space race between the US and the Soviet Union, the US spent 4.4% of its annual budget on National Aeronautics and Space Administration (NASA).[7] Today, the costs of the satellite, the launch vehicle, and the follow on ground based monitoring system continue to make space flight an expensive venture.

The Satellite

Designing and building a satellite to function in outer space is like nothing else on earth. The satellite has to be lightweight and strong. It has to be able to endure the harsh environment of space where radiation from solar flares can cause satellites to become highly charged.[8] Reliability also drives the high cost. Satellites cannot be brought back for repairs. To balance out all of these factors, satellites have become technologically sophisticated, and thus, expensive.

Exotic, lightweight materials are used, and systems are rigorously tested and certified to ensure operations. The current AFSPC commander, Gen. John Hyten, described how the military oftentimes spends between $3 billion and $5 billion to design, develop and test new satellites. “Those so-called non-recurring engineering costs come before DoD buys an operational satellite.”[9] As an example of cost, the AF recently awarded Lockheed the GPS III contract at a cost of $7.92 billion for eight satellites.[10]

The Launch

Launching a satellite into space is also expensive. When the intended satellite cargo costs billions of dollars, there is little tolerance for a launch failure. A 2010 Federal Aviation Administration (FAA) report listed the following launch vehicles and their associated costs:

- Falcon 9 - $56M
- Proton - $85M
- Delta II - $95M
- Delta IV- $100M
- Atlas V - $100M
- Ariane 5- $220M
- Delta IV Heavy - $250M[11]

All of these costs represent one time, irreplaceable costs to access space. Although Space X is working hard to build a reusable rocket and reduce this lift cost[12], the price tag for accessing space represents a barrier few but the wealthiest countries can pay.

The Ground Station

Ground mission control is an essential part of space operations in order to maintain the health and orbit of the satellite. Long after the costs of building and launching the satellite have been forgotten, the costs of maintaining satellite programs represent a continuous bill to the user. “For example, at Schriever Air Force Base in Colorado, 10 satellite programs are operated by eight separate satellite operations centers under the command of six separate space squadrons.”[13]

According to the Air Forces' FY15 Presidential Budget submission, in FY14, the Air Force spent $427M on "space control systems." This cost includes 942 DoD civilians and 1705 contractors, but does not include the active duty force of 1603 officers and 949 enlisted.[14]

Taken together, space is expensive. Since space is essential to the US, the US will continue to pay the high cost of access. However, as the next section will show, the vulnerabilities of space will force a change in how the US thinks about risks and costs in space.

Chapter 4: Space is Vulnerable

The era of the "sanctuary of space" is over. As more countries gain access to space, as the void of space fills with debris, and as technology improves to interfere with space objects from earth, the vulnerability of space assets will grow.

The growing debris problem

Space debris shows no sign of improving. The US currently tracks more than 23,000 objects in space, some as small as 10 cm. However, US sensors cannot see the estimated 500,000 pieces of debris between 1 and 10 centimeters in size.[15] The physics of space debris make the smallest pieces dangerous. In low earth orbit, a tiny fleck of paint moving at four miles per second creates the same impact force as a 550 pound object moving 60 miles per hour.[16] Almost all of the debris in space is the result of accidental events. However, the 2007 Chinese test of an antisatellite weapon "represents the most prolific and serious fragmentation in the course of 50 years of space operations" with the creation of 950 observable debris objects.[17] Until a cost effective way to reduce debris in space is determined, the cloud of debris orbiting the earth will continue to grow.

Kinetic Attack

The Chinese test in 2007 and the US destruction of the deorbiting spy satellite US 193 in 2008 represent another threat to all space assets: kinetic attack. If a country is capable of putting a satellite into orbit, they are capable of putting a weapon into orbit as well. Accurately targeting a specific object in space is a more challenging problem, but if collateral damage is not a concern, a weapon just has to get close enough to create a debris field to destroy a satellite. And imagine if the goal was to create a debris field. Almost every satellite orbits the earth in the direction of the earth's rotation because counter rotating orbits require more launch energy. But imagine a payload designed to wreak havoc in the low altitude belt by counter rotating a large debris cloud. The results would be disastrous. Kinetic attack can also be significantly more elegant. Imagine a small satellite capable of surreptitiously attaching itself to a target. Whether its goal is to destroy the target with an explosion, push it out of orbit with a thruster, or hack into the satellite itself and take it over are all within the realm of possibility.[18]

Non-kinetic Dangers

Non-kinetic weapons can be just as destructive. Directed energy systems such as lasers, jamming a satellites communications, or attacking through cyberspace can render a satellite useless. Although the power levels required to "hard kill" a satellite with a laser have not been successfully tested, lower powered lasers capable of "dazzling" a satellite have been achieved. "Chinese military writings do betray an interest in 'soft killing' of enemy satellites, as well as 'hard killing' – that is, in developing a capacity to interfere only temporarily with satellite operations and command and control, as well as to destroy an offending orbiter."[19] Cyber attacks could be conducted in a similar vain. Since all satellites communicate with the outside world in one form or another, penetrating that communication through cyber would enable an adversary to create both soft and hard kill effects. The variety of non-kinetic attacks makes them difficult to defend against.

Mitigating all of these vulnerabilities requires a variety of techniques, but they all have one thing in common: increased cost. Counter space debris solutions include improved surveillance of the debris cloud with the use of higher resolution sensors, increased hardening of the satellite's critical components with thicker, impact resistant materials, and more maneuverable satellites to get out of the way of debris. Hardening the spacecraft adds both size and weight. Adding maneuverability adds cost, weight, and in the case of a propellant driven maneuver system, decreases the useful time on orbit.

The research presented here demonstrates space is essential, expensive, and vulnerable domain. As risk in space grows, strategies to counter this vulnerability must look beyond solutions in space and come back down to earth.

Chapter 5: A Web of Drones

The benefits of space are undeniable. But when space is denied, the US must still be able to dominate and achieve victory. An alternate platform for delivering key space services is proposed here using autonomous, air refuelable drones spread out across the battlefield to form a Web of Drones (WoD). The WoD is fully described in Appendix A and offers an alternative solution to mitigating the risks of a denied space environment.

Anchoring the web

The WoD uses medium altitude unmanned drones to push space services forward from a permissive airfield. The airfield anchors the WoD's geospatial coordinate system and provides access to a high bandwidth fiber network. From this known position, the web pushes outward in a series of triangles connected by an airborne laser datalink system (ALDS). The communications function of the ALDS is discussed later, but a key function of the ALDS is its ability to determine position through triangulation. In the same way a surveyor uses lasers to triangulate a position, the aircraft uses the lasers in its ALDS to determine its position in relation to the other aircraft without GPS. Even if additional aircraft are over water or terrain with few landmarks, each aircraft will know its locations with a high degree of precision.

Autonomy

The ability of the WoD to maintain its physical presence in the air domain relies on automation. The drone does not require a pilot but autonomously launches, navigates, in-flight refuels, and lands. The aircraft is refueled using a manned refueling platform approximately every 24 hours and stays airborne for approximately 5 days. The air refueling capability is absolutely essential to extend the endurance and significantly reduce the logistics footprint of the operating base.

A Web of Capabilities

Once the web is deployed, it can continuously provide several key services previously provided by space assets. The first is precision navigation and timing (PNT). The GPS time clock has become one of the most important inputs to high bandwidth data connections. Using the ground based fiber connection on the anchor point and the ALDS aboard the aircraft, each aircraft is able to synchronize to this timing signal. It can then broadcast the signal mimicking the GPS satellite's time transmission. Navigation for air or ground assets within receiver range of the WoD is accomplished by using this timing signal coupled with the drone's knowledge of its current position.

Command and control is the next service provided by the WoD. Without space, communications are limited to ground based systems, line of sight electro-magnetic (EM) transmissions, and beyond line of sight EM transmissions such as high frequency (HF) transmissions. With the WoD linked to a ground based fiber network, each aircraft could act as a line of sight repeater to provide both voice and data to nearby aircraft and ground personnel.

The WoD expands the flow of data needed for modern, net-centric warfare. Modern aircraft with access to data via either Link-16, SADL, MADL, and IFDL are significantly enhanced when given access to additional sensors. The laser communication system of the WoD could bring a significantly higher bandwidth to the battlefield.

Finally, the drones in the WoD could switch from autonomous mode and act as remotely piloted aircraft. The command and control signal to control each plane could be transmitted within the laser links. In this mode, they could collect ISR using full motion video cameras or other sensors. They would also be capable of precision strike such as those conducted by a modern MQ-9.

Required 2040 Technologies

The WoD does not exist today because several of the key technologies are not mature enough to integrate into a fully capable system. By 2040 however, these technological hurdles could be overcome if the AF decides to pursue a WoD type solution.

Laser Communication

The ALDS currently does not exist. Fiber optic data systems have significantly improved the speed to network communications. When the fiber path is removed, two lasers can still communicate if they are aligned and the medium between the two is understood. Free space optics (FSO) studies the properties of light passing through the environment and makes steady progress both in understanding the physics of the system and the engineering required to improve capabilities. To date, the longest two-way connection has been between earth and a spacecraft orbiting the moon, a distance of 239,000 miles.[20] Airborne links have been successfully demonstrated at 115 km with a transmission rate of 3 Gbps.[21]

Air Refueling

The second critical technology for the WoD to function properly is air refueling (AR). AR improves the endurance of the web and has a significant impact on airfield operations and the logistics footprint required at the main operating base. To understand this impact, an analysis of the flight schedule required to keep the web airborne was conducted and can be found in Appendix A. The results show that without air refueling, a four-hundred mile triangle of six aircraft would require 104 sorties over 15 days for an average of 6.9 sorties per day. However, with air refueling, only 24 sorties were required over 15 days with an average of 1.6 sorties per day.[22]

Analyzing the Benefits

To help analyze the advantages, disadvantages, and opportunities of the WoD, three generalized scenarios were created. Scenario A represents an environment where air and space are both permissive. In such an environment, all space assets are fully functional and capable of accomplishing their mission. Scenario A also includes a permissive air environment. JP 3-0 Joint Operations defines a permissive environment as an "operational environment in which host country military and law enforcement agencies have control as well as the intent and capability to assist operations that a unit intends to conduct."[23] From an air perspective, the drones can operate freely. For Scenario A, both space assets and the WoD are free to conduct operations without opposition from the enemy.

Scenario B contains an environment where space is denied but air is permissive. The air environment in Scenario B is identical to the Scenario A described above. However, space assets are now completely denied and no longer operational. Although completely denying space may seem unrealistic, the goal of Scenario B is to compare the capabilities of a fully functioning WoD to the space assets they were designed to complement.

Scenario C contains an environment where both air and space are denied. The space environment in Scenario C is identical to Scenario B described above: all space is denied. The denial of air in Scenario C differs from space denial in that you cannot deny the entire air domain. Theoretically, space could become saturated with random debris to such an extent that space could be rendered unusable. The physics in the air domain are simply different. Airspace can be denied with ground and air assets that are capable of shooting down most aircraft, but as the distance increases away from this threat, the airspace becomes more permissive. For Scenario C, the airspace over the area of interest is denied, but a WoD is still capable of maintaining an airborne presence some distance away from this area.

With these scenarios in mind, the capabilities of the WoD can be analyzed.

Scenario A: Space and Air Permissive

Scenario A's permissive environment allows the capabilities of space to be fully realized. This scenario highlights what the WoD can deliver that space cannot. In the ISR category, a drone allows a sensor to get closer to the target area than a satellite. Full motion video (FMV) surveillance provided by MQ-1 and MQ-9 aircraft has proven to be an invaluable tool in the permissive environment. The closer distance also allows for the collection of SIGINT electromagnetic signals that are too weak to be detected from space. Because of the maneuverability of an airborne platform, a drone can also geolocate a target either through use of its camera or SIGINT triangulation.

In Scenario A, the WoD can also deliver a much higher bandwidth of communications than space. Although space can provide high bandwidth connectivity, an air platform must utilize a steerable dish antenna to connect to the satellite. Large, slow maneuvering platforms such as airlift, air refueling, and command and control aircraft can install such systems, but they are currently not practical for small, highly maneuverable fighter aircraft. The Joint Airborne Layer Network (JALN) is "a vision for pulling together lots of different existing networks and being able to route and transport required information to a much wider array of users."[24] With each node of the WoD acting as a miniature Battlefield Airborne Communication Node (BACN), not only would air users have access to more data through their Link-16 system, but ground users as well. David Cooper, a senior technical director at BAE Systems, noted that JALN is intended to supplement space, not replace it. "JALN might be a good opportunity to apply the emerging laser communication technologies, which uses light instead of radio spectrum to transmit 1s and 0s. The laser communications field has advanced rapidly and the hardware has shrunk in the past few years."[25] An airborne, high bandwidth, laser infrastructure would greatly supplement the space based communications in Scenario A.

Finally, modern UAS aircraft have a kinetic capability that space does not. The ability of a WoD node to find, fix, target, track, engage, and assess is the kind of multirole capability a Combatant Commander in 2040 would find indispensable.

Scenario B: Space Denied, Air Permissive

Scenario B is where the WoD could make its greatest contribution. Space denial requires US forces to find alternative paths to numerous capabilities. Perhaps the most important contribution of the WoD is precision navigation and timing (PNT). A world without GPS would be a major challenge for US forces. "There is now a mandate that Marines must conduct parts of their large-scale training exercises with degraded communications and GPS capabilities to simulate an adversary attacking space-based systems."[26] The WoD is perfectly suited to help the Marines because the goal of the WoD PNT system is to allow the GPS receivers in use today to continue to function. With known timing and position, each node in the WoD is capable of broadcasting a similar signal to the satellites in the GPS constellation. Theoretically, a web as small as three drones in a triangle would allow for the resolution of a position. For an alternate PNT solution using new inertial systems, see the following endnote.[27]

Besides PNT, the WoD could provide all of the same capabilities in a Scenario B environment that it provided in Scenario A. With space based ISR out of service, air based sensors on each aircraft could supplement airborne reconnaissance aircraft as sources of ISR. Since the aircraft are modular, different aircraft in the web could perform different functions to replace the variety of satellite collection capabilities lost in a denied space environment. With SATCOM lost in Scenario B, the WoD could be leveraged to provide high speed communication and data over as large of a footprint as the size of the web. In a permissive air but denied space environment, the capabilities of the WoD would be mission essential.

Scenario C: Space and Air Denied

The WoD capabilities decrease in the Scenario C environment in which space and localized air are denied. The drones envisioned in the WoD are undefended aircraft and not capable of operating in a denied environment. For Scenario C, with an undefended drone, some, but not all, of the capabilities in the first two scenarios will be lost. From an ISR standpoint, overhead imagery via FMV or some other method is not possible. Although EM transmissions for SIGINT could still be collected by the WoD, line of sight and attenuation due to distance and atmosphere become more of an issue. The communications and C2 relay the WoD enables would still exist, but its range would be limited to how close it could get to denied airspace. The WoD could still play a significant communication role with its ability to stretch line of sight communications across the nodes of its web. AWACS, tanker, and other aircraft not capable of entering a high threat environment could still rely on the WoD for connectivity. The physics behind the PNT capability of the WoD would not change. However, an increased distance outside of the basic WoD triangle would reduce the receiver's ability to obtain the line of sight timing signal and triangulate a position. In Scenario C, additional capabilities that require the drones physical presence over the target, such as a kinetic strike, would also be negated.

Scenario C closely resembles the Anti-Access, Area Denial (A2AD) problem the US is working hard to solve. Perhaps the best use for the WoD in an A2AD scenario would be to act as a backbone upon which other capabilities could leverage. Keeping the flow of command and control instructions, data, and reliable timing and navigation inputs flowing to the front line air, land and sea forces would counter several enemy lines of effort currently underway to deny US presence. Besides the denial of air and space, jamming of the electromagnetic spectrum prevents radio frequency communication. Since laser communication is impervious to radio frequency (rf) jamming, future aircraft could develop a way to establish laser link with the WoD to stay as close to the fight as possible. Acting as a backbone of communication and PNT support, the WoD in the A2AD environment function to provide the kind of power projection the US has grown accustomed to in a permissive environment.

Calculating 2040 costs for the WoD is nearly impossible given the required technologies to make the WoD a reality are yet to be developed. However, using an MQ-9 as a baseline and key characteristics of the WoD, a generalized cost of the overall enterprise can be estimated. The Air Force estimates the cost of the MQ-9 system as $56.5 million (FY 11) which includes four aircraft with sensors, ground control station and Predator Primary satellite link.[28] In terms of a futuristic, 2040 WoD, the drone aircraft used to build the web will not require many of the costs of a current MQ-9 fleet. Current MQ-9 aircraft require a dedicated ground station and crew to remotely fly the aircraft. Current MQ-9 aircraft operating beyond line of sight also require a dedicated satellite communications link. Neither of these two services are required for the WoD. The intelligence gathering camera of the MQ-9's costs over $1M.[29] If the WoD is not being used for ISR, the camera is not required. The ADLS would be a significant cost for each of the drone. But even if each ADLS cost $5M, it is still realistic to estimate the cost of each drone at $25M. With satellites costing from $500M to $1B, a fleet of WoD could cost the same as one satellite. Keeping a large WoD airborne would incur operations cost, but if the cost was $1M a day for fuel, that would still be cheaper for a year than the cost of many DoD satellites.

Chapter 6: Conclusion

The capabilities provided by space assets are critical. Nothing in the air domain can provide the kind of worldwide coverage of space. But space can be supplemented. The Web of Drones envisions a 2040 air based approach that provides additional capabilities when space is available and replaces localized space services when space is denied. From a cost perspective, how should the Air Force ensure the services provided by space assets are delivered in a denied environment? As long as space costs remain high and the drones described here could be produced affordably, the decision to invest in the technologies required to make the WoD a reality makes financial sense. Instead of focusing solely on space, a web of drones may provide redundancy in PNT, C2, and ISR in a future environment where the security of space is questionable.

"It is always dangerous to prophesy, particularly…about the future."[30] The Web of Drones described in this paper requires technological innovation in the field of laser free space optics, autonomous drone operations and in flight drone air refueling. But these technologies are simply a means to an ends that reduces the US reliance on space-based capabilities. The Web of Drones can be used as a theoretical baseline to launch the strategic thought out of space and back down to earth.

Appendix A

The Web of Drones (WoD) is not a new idea. One of the best examples of a futuristic WoD is the "dog pod grid" found in the Neal Stephenson's 1995 novel "The Diamond Age."

> Atlantis/Shanghai occupied the loftiest ninety percent of New Chusan's land area – an inner plateau about a mile above sea level, where the air was cooler and cleaner. Parts of it were marked off with a lovely wrought-iron fence, but the real border was defended by something called the dog pod grid – a swarm of quasi-independent aerostats.[31]

Stephenson goes on to discuss their autonomy: how they stay in position, how they share their energy, how mothership drones "called nurse drones that would cruise around dumping large amounts of power into randomly selected pods all over the grid, which would then distribute it to their neighbors."[32] So with a respectful nod to the inspiration of Mr. Stephenson, this Appendix describes the how's and why's of my implementation of a Web of Drones in 2040.

On the Design of the Aircraft

The drone is required to keep a payload airborne for 24 hours unrefueled and 5 days with refueling but without additional servicing. The drone also has to be able to cruise at 200 knots in order to spread out the web over significant distances in hours as opposed to days. The drone needs to be able to loiter relatively high to overcome the curvature of the earth, the weather and turbulence prevalent at the lower altitude, and to avoid moisture in the air which interferes with laser transmissions. These three characteristics point to a fixed wing aircraft versus a rotary aircraft or a lighter-than-air aerostat.[33]

The drone uses a propeller driven turboprop that burns jet fuel. For the long loiter times at slow airspeed, a prop is more efficient that a jet engine.[34] Jet fuel is used for its energy density, but if technology in electrical energy storage could be improved, an electric engine and battery system would be preferable. Imagine if the inflight refueling could be accomplished with a wire similar to Apple's MagSafe magnetically attached power connectors, eliminating the need for the refueling aircraft to carry and off load jet fuel.

Modular design is also important to keep the cost of the WoD down. If the WoD is not needed for ISR, leaving the $1M camera on the ground will save both weight and cost. A variety of sensors and capabilities could be incorporated and easily swapped out depending on the requirements of the mission.

A vision for ALDS: a Million Points of Light

The Airborne Laser Datalink System (ALDS) is the "silk" that connects the Web of Drones. The ALDS also represents a piece of technology that has yet to be developed. How will multiple lasers maintain a datalink on multiple maneuvering aircraft? My futuristic solution to this problem takes the form of a geodesic dome with a diameter of 1.5m mounted to the top of the aircraft. Unlike EPCOT's Spaceship Earth which has 3840 points, the ALDS would have millions of points, all representing the end of a fiber laser. The density of this dome would be such that as the laser light slowly diverged, at 200nm, the beams from two adjacent points would begin to overlap. This translates in the ability of the ALDS to always have at least one of its many surfaces capable of hitting the receiver target. To maintain the link as the aircraft maneuver, the lasers do not move. Instead, the computer determines which lasers to fire to reach the target. The fibers also act as receivers, capturing energy across its 1.5 m diameter. In this way, each ALDS could act as a node for numerous laser transmissions. Finally, the dome would be collapsible to produce less drag for transition and to aide in in-flight recovery.

On the need for Air Refueling

In regards to in-flight refueling, the RQ-4 Global Hawk has already demonstrated the ability to hold the pre-contact air refueling position.[35] But the 2040 drone aircraft will be capable of so much more. Imagine a C-17 type aircraft not only being able to offload fuel to the drone, but to capture the drone in midair and bring it inside the cargo compartment. The ability to do maintenance while airborne, change out sensors, or rearm the aircraft would drastically improve the versatility of the drone.

The WoD proposed in this paper deploys aircraft in a triangular formation with orbits that are 200 nm apart. The Air Forces current fleet of MQ-1 and MQ-9 RPAs would be capable of sustaining such an orbit, but the penalty of aircraft without an AR capability would be the increased airfield activity and the number of drones required. The 2040 aircraft proposed for the WoD can stay airborne for 24 hours and can transit at 200 knots. The anchor aircraft that flies over the field and provides the connection to the terrestrial fiber could be on station in about 30 minutes after takeoff. Even with only a 30 minute transit time, to maintain 24 hour coverage, 16 sorties are required to maintain 15 days of coverage. As the transit time increases, so does the number of sorties required to maintain coverage. Two hours of transit time (approximately 400 miles) would require 18 sorties over 15 days. Five hours of transit time (1000 miles) would require 26 sorties over 15 days. Tables 1 below shows a theoretical flight schedule of 26 sorties for this 1000 mile node point when air refueling is not available. Table 2 shows the same node being serviced by seven air refuelable drones. Without air refueling, a four-hundred mile triangle of six aircraft would require 104 sorties over 15 days for an average of 6.9 sorties per day. However, with air refueling, only 24 sorties were required over 15 days with an average of 1.6 sorties per day

Table 1. Sorties Required without Air Refueling

Sortie	TO	On Station	Off Station	Land	Transit	Station Time
Z1	1/1/15 12:00	1/1/15 17:00	1/2/15 7:00	1/2/15 12:00	5:00	14:00
Z2	1/2/15 2:00	1/2/15 7:00	1/2/15 21:00	1/3/15 2:00	5:00	14:00
Z3	1/2/15 16:00	1/2/15 21:00	1/3/15 11:00	1/3/15 16:00	5:00	14:00
Z4	1/3/15 6:00	1/3/15 11:00	1/4/15 1:00	1/4/15 6:00	5:00	14:00
Z5	1/3/15 20:00	1/4/15 1:00	1/4/15 15:00	1/4/15 20:00	5:00	14:00
Z6	1/4/15 10:00	1/4/15 15:00	1/5/15 5:00	1/5/15 10:00	5:00	14:00
Z7	1/5/15 0:00	1/5/15 5:00	1/5/15 19:00	1/6/15 0:00	5:00	14:00
Z8	1/5/15 14:00	1/5/15 19:00	1/6/15 9:00	1/6/15 14:00	5:00	14:00
Z9	1/6/15 4:00	1/6/15 9:00	1/6/15 23:00	1/7/15 4:00	5:00	14:00
Z10	1/6/15 18:00	1/6/15 23:00	1/7/15 13:00	1/7/15 18:00	5:00	14:00
Z11	1/7/15 8:00	1/7/15 13:00	1/8/15 3:00	1/8/15 8:00	5:00	14:00
Z12	1/7/15 22:00	1/8/15 3:00	1/8/15 17:00	1/8/15 22:00	5:00	14:00
Z13	1/8/15 12:00	1/8/15 17:00	1/9/15 7:00	1/9/15 12:00	5:00	14:00
Z14	1/9/15 2:00	1/9/15 7:00	1/9/15 21:00	1/10/15 2:00	5:00	14:00
Z15	1/9/15 16:00	1/9/15 21:00	1/10/15 11:00	1/10/15 16:00	5:00	14:00
Z16	1/10/15 6:00	1/10/15 11:00	1/11/15 1:00	1/11/15 6:00	5:00	14:00
Z17	1/10/15 20:00	1/11/15 1:00	1/11/15 15:00	1/11/15 20:00	5:00	14:00
Z18	1/11/15 10:00	1/11/15 15:00	1/12/15 5:00	1/12/15 10:00	5:00	14:00
Z19	1/12/15 0:00	1/12/15 5:00	1/12/15 19:00	1/13/15 0:00	5:00	14:00
Z20	1/12/15 14:00	1/12/15 19:00	1/13/15 9:00	1/13/15 14:00	5:00	14:00
Z21	1/13/15 4:00	1/13/15 9:00	1/13/15 23:00	1/14/15 4:00	5:00	14:00
Z22	1/13/15 18:00	1/13/15 23:00	1/14/15 13:00	1/14/15 18:00	5:00	14:00
Z23	1/14/15 8:00	1/14/15 13:00	1/15/15 3:00	1/15/15 8:00	5:00	14:00
Z24	1/14/15 22:00	1/15/15 3:00	1/15/15 17:00	1/15/15 22:00	5:00	14:00
Z25	1/15/15 12:00	1/15/15 17:00	1/16/15 7:00	1/16/15 12:00	5:00	14:00
Z26	1/16/15 2:00	1/16/15 7:00	1/16/15 21:00	1/17/15 2:00	5:00	14:00

Table 2. Sorties Required with Air Refueling

Sortie	TO	On Station	Off Station	Land	Transit	Station Time
Z1	1/1/15 12:00	1/1/15 17:00	1/6/15 7:00	1/6/15 12:00	5:00	110:00:00
Z2	1/6/15 2:00	1/6/15 7:00	1/10/15 21:00	1/11/15 2:00	5:00	110:00:00
Z3	1/10/15 16:00	1/10/15 21:00	1/15/15 11:00	1/15/15 16:00	5:00	110:00:00
Z4	1/15/15 6:00	1/15/15 11:00	1/20/15 1:00	1/20/15 6:00	5:00	110:00:00
Z5	1/19/15 20:00	1/20/15 1:00	1/24/15 15:00	1/24/15 20:00	5:00	110:00:00
Z6	1/24/15 10:00	1/24/15 15:00	1/29/15 5:00	1/29/15 10:00	5:00	110:00:00
Z7	1/29/15 0:00	1/29/15 5:00	2/2/15 19:00	2/3/15 0:00	5:00	110:00:00

On the logistical benefits of Air Refueling

The logistical footprint for a six point WoD would be similar to the current MQ-1 footprint required to support six orbits. The current technique to determine the number of aircraft required uses the equation:

$$\text{Required Aircraft} = (2 \times \text{Required Orbits}) + 2$$

Each orbit plans on one aircraft being airborne with one on the ground to launch and replace it. The "plus two" helps manage spare aircraft and when longer term maintenance is required. This model is useful today when the orbits are less than 24 hours meaning there are never two aircraft airborne for any given orbit. However, the WoD would require more than one aircraft airborne to maintain a 24 hour on-station time. A more accurate required aircraft number for the WOD without AR would use the average number of sorties per day in an equation that looks like the following:

$$\text{Required Aircraft} = (2 \times \text{Average Sorties Per Day}) + 2$$

For the six orbit WoD described above requiring 6.9 sorties per day, 16 aircraft would be required at the main operating base. In an expeditionary environment, ramp space is usually at a premium. In a hostile environment, ramp space is a liability that exposes the aircraft to the threat of attack.

When the drones are capable of aerial refueling (AR), not only do the sortie generation numbers decrease, but the logistics footprint of the main operating base decreases as well. The proposed 2040 aircraft used in the WoD can stay airborne for five days after it is refueled four times (once every 24 hours). When simulated flight plans were developed for the six orbit WoD described above, each orbit only required four sorties to cover a 15 day period.

Table 3. Aircraft Required Comparison

Distance from Base	Non AR Capable	AR Capable
Anchor	16	4
200	17	4
346	18	4
400	18	4

What took 104 sorties over 15 days without air refueling now only takes 24, for an average of 1.6 sorties per day. This low sortie rate allows the total number of aircraft required to decrease as well. Air refueling would allow the required aircraft equation to be reduced to:

Required Aircraft = (Required Orbits) + 3

The "plus three" in this case would allow for a launch and a spare each day plus one additional aircraft to handle longer term maintenance. For the six orbit WoD described here, only nine AR capable aircraft would be required.

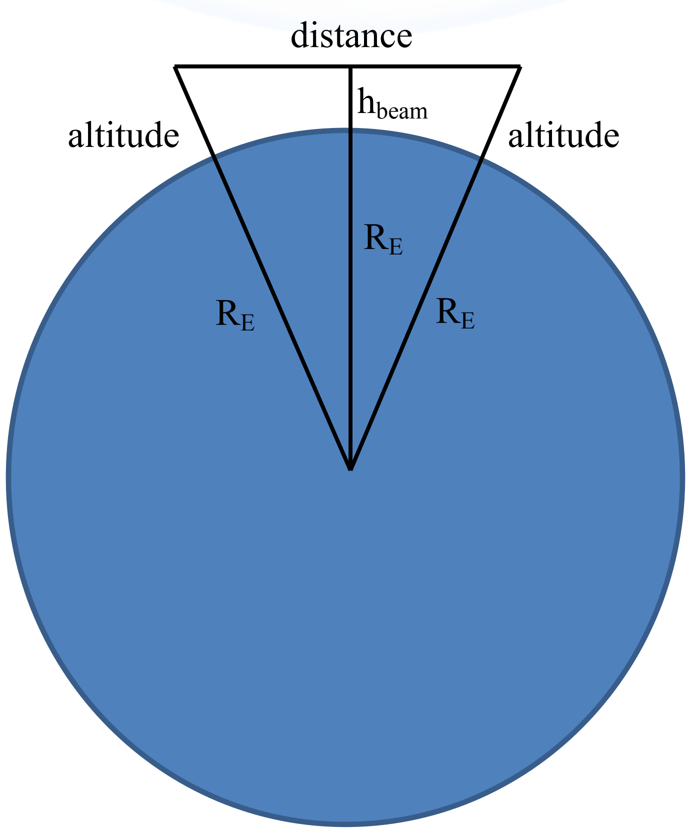
On the In-Flight Replenishment

Besides inflight refueling, inflight replenishment and maintenance could also be possible. A system could be designed where the refueling aircraft "grabbed" the drone with a crane like arm. The wings of the drone could fold back and the drone could be brought into the cargo hold of the aircraft. From here, weapons could be reloaded, sensors changed, or even minor maintenance could be performed. Instead of losing an aircraft due to an impending engine failure, the aircraft could be captured by this "mothership" and returned to base.

On the Design of the Web

The altitude of the drones and the distance between them are not set in stone. A denser web (more nodes, shorter distances between nodes) will provide greater capabilities. However, if the goal is covering large expanses of distance, the least number of nodes will provide the greatest economy of force. In an attempt to find an optimum altitude and distance, I wanted to make sure the laser links stayed above 20,000 ft.(h_{beam} in Figure 1 below) Laser energy is significantly impacted by weather and water vapor. Staying above 20,000 ft. keeps the majority of water vapor below the links. I also wanted the drone aircraft to stay in the 20,000 to 30,000 altitude range. This is due to the nature of turboprop engines as their performance tends to decline above 30,000 ft. So, with the distance of h_{beam} set at 20,000ft and altitude set at 30,000ft, I solved for distance based on the a very crude spherical model of the curvature of the earth. I then rounded all the numbers out for ease of description. So, when distance equals 200 nm and altitude equals 30,000ft, h_{beam} equals 21,179 ft.

Figure 1: Curvature of the earth analysis



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[27] Providing PNT in this manor represents an alternative method to a path the US is pursuing involving a very sensitive, very small, self-contained inertial system. DARPA is "trying to reduce the military's reliance on Global Positioning System (GPS) satellite guidance for advanced munitions, mid- and long-range missiles, and other weapons by creating a navigation-system-on-a-chip that combines traditional and atomic inertial guidance technology." Such a system is warranted for systems and munitions that require a high degree of precision in a potentially hostile environment. A system on a chip inertial navigation system (INS) would be very useful for the WoD as well as a backup for the laser triangulation technique used to calculate position. However, one of the goals of the WoD is to supplement space in a cost effective manner. An INS on a chip would be required for every device that requires navigation information. The Air Force fleet may be capable of such a modification, but all of the ground assets, both military and civilian, that rely on GPS would require a significant investment. See John Keller, "DARPA seeks to wean smart weapons off GPS with hybrid inertial navigation

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